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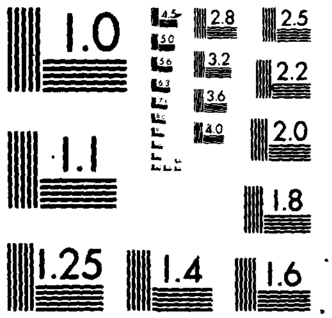

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ONBOARD ACOUSTIC DATA-PROCESSING FOR THE STATISTICAL ANALYSIS OF ARRAY BEAM-NOISE

by

RONALD A. WAGSTAFF

15 DECEMBER 1980

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ONBOARD ACOUSTIC DATA-PROCESSING FOR THE STATISTICAL ANALYSIS OF ARRAY BEAM-NOISE

by

(10) Ronald A. Wagstaff

(11) 15 December 1980

This memorandum has been prepared within the SACLANTCEN Underwater Research Division as part of Project 21.

O.F. Hastrup

O.F. Hastrup
Division Chief

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ONBOARD ACOUSTIC DATA-PROCESSING FOR THE STATISTICAL ANALYSIS OF ARRAY BEAM-NOISE

by

Ronald A. Wagstaff

ABSTRACT

A software package for onboard acoustic data-processing in the statistical analysis of array beam noise has been implemented on a mini-computer system. The package produces products both to assess data quality and to measure the noise-field's statistical characteristics. Many of the products are sufficiently general to have application to other types of data or to satisfy other objectives. The various outputs are described and illustrated by results from simulated measurements of the ambient noise by a towed array. The simplified run procedure is included to facilitate the use of the software package by the analyst.

INTRODUCTION

Over a period of several years, experience gained through participation in measurement exercises and the resulting data analyses has led to the development of a "standard" software package for onboard statistical analysis of time-series data. Although in the past, the data have been of beam noise acquired by towed arrays, many of the products are sufficiently general to apply to data acquired by other systems, even a single hydrophone. The purpose of this memorandum is to describe the capabilities and products of this software package.

The software package was developed with two goals in mind. The first, described in Ch. 2, was to enable an assessment of the data quality. This requires routines that can address the performance of the sonar system as a measurement tool and others that can assess the character of the ambient-noise field at the time of the measurement. In other words, how did the condition of the measurement tool affect the measurements and was the noise field sufficiently "well behaved" to enable meaningful results to be obtained? The second objective, described in Ch. 3, was to provide products that could be useful in the characterization and the analysis of the noise field. Some products satisfy both purposes but are discussed only once. Some, such as the mean level, are commonly used and need little or no explanation, so that the discussions of them are appropriately brief. For less well-known products, the discussions are sufficient to give only an idea of their form, utilization, and utility; more thorough discussions can be obtained from the references.

1 INPUT DATA

The input data are in the form of decibel-level time series. At present, the input capacity is limited to 66 time-series of 240 points each. For one particular system of the recent past, this corresponds to six hours of narrow-band data for 64 beams and two hydrophones. The total amount of data, and hence the total time, could be increased substantially by exercising the program's built-in capability to form averages of the input data before storing and execution. In this way the data-acquisition time could be extended to more than 60 hours if, for example, 240 averages of 10 samples each were used.

The experimental procedure by which the data are collected and analyzed is as follows. Long duration (2 to 12 hour) tows are made on one heading to acquire data to determine the statistics of towed-array beam noise. Data are also collected while on various array headings to obtain estimates of noise-field spatial statistics, i.e. noise-field horizontal directionality. Table 1 illustrates a typical set of array headings at one site during noise measurements. The arrows are vector displacements, with the magnitude of the shortest being the distance the array travels in one hour (about 4 n.mi). Thirty minutes are used for array stabilization after a turn and the other thirty minutes for data collection.

For the purpose of illustration, a typical ambient-noise measurement exercise was simulated with the aid of a Hewlett-Packard minicomputer and Interactive Time-Series Analysis (ITSA) software. Two noise sources were simulated in a background of white noise. One source was always along a bearing of 090° true. The other was always at 000° relative. The first simulates a distant target or relatively stationary noise source. The second simulates the interference caused by the towship noise. Forty channels of data were generated and spectrum analyzed to give about 10 Hz resolution. The resulting data were then beamformed in the frequency domain by performing a 64-point (the last 24 points are zeroes) spatial fast-Fourier transform. This resulted in 64 sets of time-series of beam-noise complex coefficients for each measurement period (or array heading). In all, six different headings of data were collected and processed. The majority of the examples used herein are from this simulated noise-measurement exercise.

2 ASSESSMENT OF DATA QUALITY

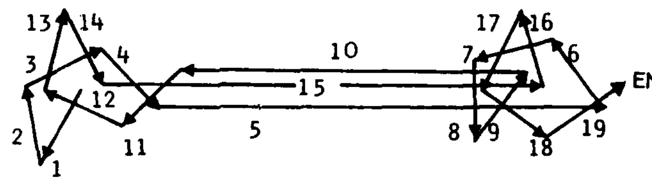
The measured data are the basic foundation on which rests the interpretation of results and formulation of conclusions. When the quality of the data is low or uncertain, the level of confidence in the correct interpretation of the results and formulation of conclusions must also be low. Data quality can be a severe problem when the phenomenon being measured is as highly variable as ambient noise. The severity is compounded when the measurement system is a towed line array, which always has its own interfering source (towship) and is not constrained to remain linear, horizontal, or on a given heading.

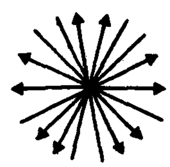
For these reasons the following products for the assessment of data quality have been included in the software. They are each described more fully in

TABLE 1

TYPICAL TOWSHIP MANOEUVRES DURING A NOISE MEASUREMENT EXERCISE WITH A TOWED ARRAY

The arrows are vector displacements. The lengths of the shortest vectors correspond to the distance the towship can travel in one hour (about 4.5 n.mi)





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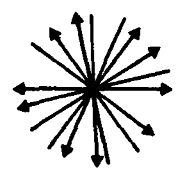

POLYGON B

LEG NO.	RELATIVE HEADING (°)	HEADINGS (°) FOR SITE G1	G2
1	115	200	205
2	157	242	247
3	335	260	065
4	045	130	135
5	000	085	090
6	235	320	325
7	165	250	255
8	087	172	177
9	305	030	035
10	180	265	270
11	135	220	225
12	205	290	295
13	283	008	013
14	065	150	155
15	000	085	090
16	255	250	345
17	113	108	203
18	035	030	125
19	325	320	055

the sections of this chapter, as follows:

- Plot of hydrophone average noise level versus hydrophone number (test for hydrophone operation), see Sect. 2.1.
- Average beam power level (indication of contaminating sources or poor beamforming), see Sect. 2.2.
- Standard deviation of beam and hydrophone levels (erratic beamformer or hydrophone output), see Sect. 2.3.
- Number-of-Runs Test (test for randomness in each time series), see Sect. 2.4.
- Mean Squared Successive Difference Test (test for transients in a time series), see Sect. 2.5.
- Kendall's Rank Correlation Coefficient (linear trend detector), see Sect. 2.6.
- Spearman's Rank Correlation Matrix (test for towship dominating sidelobes), see Sect. 2.7.
- Beam polar plots of the median noise level (anomalous persistent beam-noise response patterns are easily spotted, available only when noise directionality is estimated), see Sect. 2.8.

2.1 Plot of Hydrophone Average Noise Level versus Hydrophone Number

An inverse fast-Fourier transform (FFT) is performed on the beam-noise complex coefficients to get back to the hydrophone data. The average level is then calculated for each hydrophone for up to five frequencies and is plotted as in Fig. 1. Anomalous behaviour, which influences the mean level of some of the hydrophones, is easily detected at a glance in such a plot. For example, the last 24 of the 64 hydrophones were simply zeroes to facilitate a 64-point FFT with 40 hydrophones. These appear the same in the plot as would "dead" hydrophones. A reduction in sensitivity of a hydrophone, a faulty preamplifier, or any other fault in the acoustic channel would likewise be readily apparent.

2.2 Average Beam Power Level

The level of the average power is calculated for each beam-time series (see Fig. 2 col. 12). When this parameter is anomalously high or low, or out of range with the corresponding values for other beams, it is an indication of a possible problem. Data contamination due to a nearby ship (including the towship) or poor beamforming (i.e. bad channels or array nonlinearity) are possible causes.

2.3 Standard Deviation of Beam and Hydrophone Levels

The standard deviation, being a measure of the spread of the data, can be an extremely useful indication of biased data. For example, an abnormally high value could be due to a ship entering or leaving the sector of a beam or to the array wandering (snakeing) during the measurement period. Such data could not be considered stationary and may place limits on their

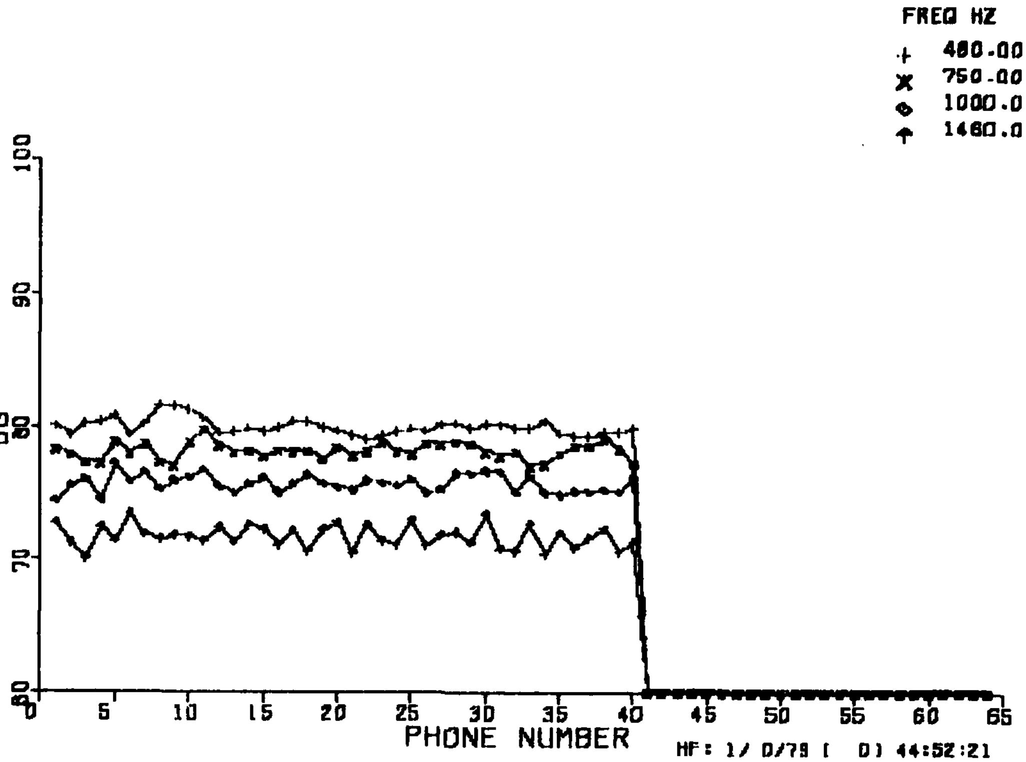

FIG. 1 HYDROPHONE NOISE LEVEL VS HYDROPHONE NUMBER PLOT FOR FIVE FREQUENCIES

DATE 1/ 0/1980 SAMPLE SIZE 42
TACTIC 1 LEG 3
ST. TIME = 0 0. 0 HEADING = 233
FREQUENCY = 160.00 GAIN = 0.0
SOUND SPEED =1500. SIDELOBE = 30.0
LONG= 0 0.00 N LAT= 0 0.00
DEPTHS = 0 0 0 0 0 M.
WEIGHT = UNIFORM
ARRAY = MID
# AVG = 5

BEAM	RHDG	THDG	THDG	BW	10%	25%	MEDIAN	75%	90%	AVG	AVGPR	STDEV	SKEW	KURT	OB	ZRUN	ZMSSD	ZTAU
22	7.1	240.1	225.9	14.24	70.3	72.6	74.2	75.5	77.1	74.0	74.6	2.28	-.27	-.73	42	0.000	.849	-1.690
23	23.9	256.9	209.1	14.23	66.1	67.3	68.6	69.7	71.2	68.6	69.0	1.99	-.44	-1.44	40	.320	1.493	-2.291
24	36.6	269.6	196.4	8.59	57.9	59.2	60.6	61.9	62.6	60.6	60.9	1.79	.05	-1.22	42	-1.250	-.431	-1.389
25	45.5	278.5	187.5	7.10	55.4	56.8	58.3	59.9	61.3	58.4	58.8	2.10	-.09	-.47	42	-.312	-1.362	-1.373
26	53.1	286.1	179.9	6.31	58.0	59.2	60.1	61.9	62.7	60.3	60.6	1.68	-.02	-2.24	42	-.312	-1.262	.524
27	60.0	293.0	173.0	5.82	50.1	53.1	55.1	56.6	57.7	54.7	55.3	2.43	-.47	-.36	42	-.925	-1.344	.044
28	66.4	299.4	166.6	5.50	53.1	55.6	56.7	57.5	58.8	56.4	56.8	1.97	-.86	-.58	42	2.500	1.305	.415
29	72.6	305.6	160.4	5.28	52.5	54.5	56.4	57.3	57.9	55.9	56.3	1.93	-.67	-.80	42	1.250	.941	-.534
30	78.5	311.5	154.5	5.14	51.6	53.4	55.2	56.6	56.8	54.8	55.2	1.98	-.69	-1.81	42	0.000	.978	.251
31	84.3	317.3	148.7	5.06	55.4	56.7	57.4	58.4	59.8	57.6	57.8	1.66	-.66	2.62	39	-.808	.649	-1.514
32	90.0	323.0	143.0	5.03	54.4	55.9	56.8	58.0	58.5	56.8	57.0	1.57	-.24	-.98	42	-1.562	-1.308	-.284
33	95.7	328.7	137.3	5.06	55.4	56.3	57.2	58.2	58.9	57.1	57.3	1.34	-.12	-12.52	42	.312	1.499	-.033
34	101.5	334.5	131.5	5.14	51.4	53.2	55.0	56.5	57.3	54.8	55.4	2.18	-.16	-.01	40	-.961	-.926	-.185
35	107.4	340.4	125.6	5.28	52.7	53.8	55.6	56.4	57.3	55.3	55.6	1.69	-.60	1.53	42	0.000	.152	.590
36	113.6	346.6	119.4	5.50	56.6	58.3	60.3	62.4	63.3	60.3	61.0	2.59	-.19	-1.24	42	-.937	-1.165	-.174
37	120.0	353.0	113.0	5.82	56.7	58.3	59.8	60.5	61.1	59.2	59.6	1.81	-1.14	.96	41	-.787	1.627	-.799
38	126.9	359.9	106.1	6.31	60.4	62.5	63.5	64.3	65.0	63.2	63.5	1.80	-1.18	4.03	40	-1.602	-.305	-.818
39	134.5	7.5	98.5	7.10	65.0	66.8	68.3	69.4	70.0	68.0	68.3	1.82	-.68	2.58	42	-.937	.296	1.198
40	143.4	16.4	89.6	8.59	70.8	73.0	74.1	75.4	75.8	74.0	74.4	1.96	-.68	1.97	42	.312	-.377	.164
41	156.1	29.1	76.9	14.23	64.7	66.9	68.4	69.6	70.3	68.1	68.6	2.20	-.62	.12	42	.312	-.217	.219
42	172.9	45.9	60.1	14.24	59.8	61.5	62.8	64.0	64.8	62.7	63.1	1.75	-.09	2.18	42	-.312	-.454	-.011
65	0.0	0.0	0.0	0.00	77.3	78.2	78.6	79.3	79.7	78.6	78.7	.87	-.29	-88.81	39	.527	-.106	-1.066
66	0.0	0.0	0.0	0.00	75.5	76.7	78.6	79.9	80.6	78.3	78.7	1.87	-.26	1.00	39	-1.133	-.100	.131

BEAM 65 IS THE MEDIAN PHONE
BEAM 66 IS PHONE 32

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FIG. 2 EXAMPLE TABULAR OUTPUT FOR SOME BEAM AND HYDROPHONE NOISE TIME SERIES QUALITY ASSESSMENT AND STATISTICAL ANALYSIS PRODUCTS usefulness. On the other hand, a standard deviation that is too small could be an indication of equipment malfunctioning or improperly set up. Figure 2, col. 13, illustrates typical output.

2.4 Number-of-Runs Test

The number of runs in any time-series of beam-noise measurements is a non-parametric statistic (i.e., a statistic that is independent of the actual distribution function for the data set under investigation). The number of runs is used as one measure of randomness in a series of observations. The attribute under consideration is randomness in the arrangement of beam-noise levels in a time-series and not in the distribution of beam-noise level magnitudes. Consequently, the number-of-runs statistic indicates the temporal randomness of the process that generated the noise levels observed at the beamformer output (i.e. the randomness of the beam-noise data in the time domain).

In order to actually calculate the number-of-runs statistic <1>, beam-noise levels in the time-series must be transformed into three categories, according to whether they are:

- above the median beam-noise level (A's)
- below the median beam-noise level (B's)
- equal to the median beam-noise level (M's).

Individual beam-noise levels in the time-series are then replaced by the symbols A, B or M. Subsequently, samples equal to the median value (M's) are eliminated from the data set. Any unbroken sequence of like kinds (e.g., AA, BBB, etc.) in the revised time-series is counted as one run. The number of runs in the time-series, regardless of the length of the run, is then counted. The algorithm relates the number of runs actually counted (RUN) to the distribution of runs expected for any randomly distributed time-series containing (N_A) A elements and (N_B) B elements. Assuming that all the elements of the time-series have the same probability of occupying any position in the temporal sequence, a probability distribution for each realizable permutation of the A's and B's can be determined. Mathematically, the expected distribution of the number of runs in a large sample drawn from a randomly-distributed population can be approximated by a normal distribution of the variable R, with the mean and standard deviation values given by

$$R = \frac{2N_A N_B}{N_A + N_B} + 1$$

$$\sigma^2 R = \frac{2N_A N_B(2N_A N_B - N_A - N_B)}{(N_A+N_B)^2 (N_A+N_B-1)} .$$

The algorithm employed in the software calculates the quantity ZRUN (see Fig. 2, col. 17), which expresses the number of runs actually counted (RUN) in terms of the statistics for the corresponding normal distribution:

$$ZRUN = \frac{RUN - R}{\sigma_R} .$$

That is, ZRUN is the deviation of the actual number of runs from the expected mean, normalized in terms of the expected standard deviation. Beam-noise time-series with too few or too many runs (i.e., those with large values of the parameter ZRUN) are suspected to be products of non-random processes. It should be noted that a completely deterministic signal – such as an acoustic tone – could produce too few or too many runs, depending on its frequency, since the sampling interval is generally constant.

The ZRUN term can be used directly to eliminate beam-noise data sets that appear to have too few or too many runs. For example, one could arbitrarily state that any time-series with ZRUN > 2 should be eliminated from further consideration. However, since the expected distribution of the number of runs is normal, approximately 4.5% of the valid data would be rejected by such a criterion. An alternate and perhaps more appropriate screening method would eliminate data sets based on the confidence level associated with the hypothesis that the measured number of runs (RUN) is, in fact, a member of the normal distribution (R, σ_R^2).

2.5 Mean-Square Successive Difference Test

The Mean-Square Successive Difference (MSSD) Test attempts to verify that each measurement of beam-noise level in any particular time-series is independent of the next (successive) measurement in that time-series. Unlike the Number-of-Runs Test, the MSSD Test (Fig. 2, col. 18) uses the numerical value of each measured noise level as well as its relationship to the adjacent (successive) measurement in the time-series. The test is particularly valuable in identifying contamination of time-series data due to transients of both acoustic and non-acoustic origin.

The Mean-Square Successive Difference Test is based on the assumption that the measurements in any time-series are drawn from a normally distributed population with unknown mean and variance. Under this assumption, two methods can be used to estimate the population's variance, σ^2. One is the unbiased estimator:

$$s^2 = \frac{1}{N-1} \sum_{i=1}^{i=N} (x_i - x)^2$$

The other is:

$$\frac{d^2}{2} = \frac{1}{2(N-1)} \sum_{i=1}^{i=N-1} (xi+1 - xi)^2 ,$$

one-half of the mean of the successive differences squared. If the time-series data are dependent or are not drawn from a normally distributed population, the two calculations should produce different estimates of the variance. For example, if the beam-noise time-series measurements are accumulated during periods containing steadily increasing or decreasing noise levels (i.e., an upward or downward sloping ramp), the differences between consecutive samples would be smaller than those obtained for a completely random noise field. Hence the $d^2/2$ estimate of the variance would be smaller than that calculated using the unbiased estimator.

When the beam-noise measurements contain strong, constant signals, the two estimates may or may not be significantly different. If the strong signal persists throughout the entire measurement interval, the two estimates would be nearly identical, since all the x_i levels are nearly uniform. However, if the strong signal is present only during a significant fraction of the measurement interval, the results produced by the two variance estimators will be substantially different. For these reasons, the MSSD Test may be viewed as a detection device for certain kinds of transient signals in the time-series data.

The algorithm employed calculates the test statistic ZMSSD, where:

$$\text{ZMSSD} = \frac{d^2/2s^2 - 1}{[(N-2)/(N^2-1)]^{\frac{1}{2}}}$$

If the assumptions concerning the beam-noise measurements are valid, the expected distribution of the test statistic ZMSSD can be approximated by a normal distribution with a mean value of zero and a unit variance.

The exact distribution of this test statistic has been tabulated for uncorrelated observations with sample sizes ranging from 4 to 60 <2>. For sample sizes greater than six, the normal distribution is a very good approximation at the 0.05 and the 0.95 significance levels. However, the normal distribution is not a good approximation of the exact distribution at the 0.001, 0.01, 0.99, and 0.999 significance levels until the sample size is greater than 60. Nonetheless, the normal distribution is a useful approximation, since it always yields conservative estimates. To indicate the magnitude of the differences, critical values of ZMSSD were calculated at various confidence levels using the normal approximation. Table 2 compares the results with the exact values (from <2>) for a sample size of 60:

TABLE 2

COMPARISON OF ZMSSD RESULTS WITH EXACT VALUES

Critical Values based on	Significance Levels					
	0.001	0.01	0.05	0.95	0.99	0.999
Approximate normal distribution	-3.091	-2.327	-1.645	1.645	2.327	3.091
Exact distribution	-3.013	-2.306	-1.649	1.649	2.306	3.014

Since the accuracy of the normal distribution approximation improves as the sample size increases, the approximation should be more than adequate for beam-noise sample sizes of 60 or more.

MSSD Test results (i.e., the quantity ZMSSD) are interpreted and used in much the same manner as the Number-of-Runs Test results (ZRUN). The quantity ZMSSD can be used directly to eliminate data sets from further processing actions or it may be used to test the hypothesis that the beam-level measurements contained in any time-series are distributed in a random manner (i.e., are not correlated). In the latter case, tabulated critical values for the appropriate normal distribution are required to confirm (or reject) the statistical hypothesis.

2.6 Kendall's Rank Correlation Coefficient

The Kendall rank correlation coefficient is a non-parametric (distribution free) statistic that provides a measure of the correlation between two sets of ranked observations <3>. Kendall's rank correlation coefficient is used to measure the correlation between each time-series of beam-noise measurements and a set of monotonically increasing integers (1, 2, 3,...,N). The monotonically increasing data set used for each correlation assessment is identical to the ranked order of any continuously increasing function. Therefore, increasing trends in any time-series of beam-noise measurements result in positive values of the correlation coefficient, while decreasing trends produce negative values. The absolute magnitude of the correlation coefficient provides an indication of the duration of the trending portion of the time-series relative to the length of the sample under consideration. Although the concept is similar in some respects to the number-of-runs statistic, the Kendall rank correlation coefficient uses much more of the information present in the time-series and is considerably more powerful (in a mathematical sense) than the ZRUN and ZMSSD results described previously.

In order to calculate Kendall's rank correlation coefficient, each observation in the time-series must be replaced by its ranking relative to all other measurements in that particular time-series. As used here, the term 'rank' implies that all measurements in the time-series can be rearranged in a monotonically increasing sequence from the minimum to the maximum value (i.e., ordered according to the magnitude of the measurements). Each measurement value is then assigned a numerical rank and, in turn, the numerical ranks are substituted into the original time-series in place of the measured values. Multiple occurrence of certain values in the original time-series (i.e. tied data points) complicates the process, since it requires somewhat more bookkeeping, but the end result is essentially the same. Ties are treated in the usual manner and are assigned the same fractional rank. For example, if there is an n-way tie for the rank r_i, the numerical rank assigned to each of these values is:

$$\frac{r_i + r_{i+1} + r_{i+2} + \dots + r_{i+n-1}}{n} .$$

Consequently, the next rank available for use in the sequence is r_{i+n}. In either case, the resultant sequence of numbers presents the numerical rank of each value in the original time-series relative to all others in that series.

Numerical data for the calculation process are obtained by examining the relationship between each pair of ranks in the modified time-series (r_a, r_b, r_c, r_d, ..., r_u), beginning with the element r_a. The u-1 pairs containing r_a [(r_a, r_b), (r_a, r_c), ..., (r_a, r_u)] are examined first, then the u-2 pairs containing r_b [e.g., (r_b, r_d), ..., (r_b, r_u)] are considered, and so on until the end of the sequence is reached. A score of +1 is assigned to each pair having the ranks in ascending order (e.g., the pair 2, 6) while a score of -1 is assigned to each pair having the ranks in inverse order (e.g., the pair 7, 5). Scores for each individual pair are summed to obtain the total score (S) for the modified time-series. If there are no tied data points, the Kendall rank correlation coefficient, τ, is defined by the following:

$$\tau = \frac{\text{total score}}{\text{maximum possible score}} = \frac{S}{\frac{1}{2}N(N-1)},$$

where

N = the number of measurements in the time-series.

When there are tied data points, the Kendall rank correlation coefficient is defined by:

$$\tau = \frac{S}{[\frac{1}{2}N(N-1)]^{\frac{1}{2}}\,[\frac{1}{2}N(N-1) - T]^{\frac{1}{2}}},$$

where

$T = \frac{1}{2}\Sigma t_j(t_j - 1)$, and

t_j = the number of elements in the jth group of tied data points.

The Kendall rank correlation coefficient can have any value from +1 to -1. If the series of ranks is a monotonically ascending sequence from 1 to N, it is obvious that τ will be equal to 1. Similarly, if the series of ranks is a monotonically descending sequence from N to 1, it is clear that τ will be equal to -1. The value of τ observed in any time-series may be used directly as a criterion to eliminate highly correlated data sets. For example, any time-series could be considered unsuitable for deconvolution processing if $\tau > \tau_{max}$.

As stated at the outset, the Kendall rank correlation coefficient is used to detect trends in time-series data. Consequently, the expected distribution of τ must be determined for samples drawn from a randomly-distributed population. Assuming that each element of the time-series has an equal probability of occupying any position in the temporal sequence, then the expected probability distribution of the parameter τ can be developed for every sample size N. Indeed, such tables are available – even for moderately large sample sizes (i.e., N < 40). For larger samples from a randomly-distributed population, the parameter τ can be considered as a normally distributed variate with a mean value of zero and a variance of:

$$\sigma_\tau^2 = \frac{2(2N + 5)}{9N(N-1)} .$$

The algorithm employed in the onboard acoustic data-processing software calculates the quantity ZTAU (Fig. 2, col. 19), which expresses the Kendall rank correlation coefficient actually observed (τ) in terms of the parameters for the expected distribution:

$$\text{ZTAU} = \frac{\tau}{\sigma_\tau} .$$

The statistic ZTAU is interpreted and used in much the same manner as the terms ZRUN and ZMSSD described previously. Each is a normally distributed variate with a mean value of zero and a unit variance. They are used in conjunction with tabulated values for the normal distribution to confirm or reject statistical hypotheses relating the time-series under consideration with a known (normal) probability distribution.

2.7 Spearman's Rank Correlation Matrix

The degree of association between two series of measurements can be estimated by calculating the Spearman's rank correlation coefficient, r_s <4>. This statistic can be used to measure the correlation between noise-measurement sequences obtained simultaneously on any two beams. Consequently, if any two series of beam-noise measurements are highly correlated, there is a corresponding probability that a common noise source is the cause of both sets of measurements. An example is when the noise from the towship dominates the low-noise-level beams: comparing the low-noise-level beam with one receiving the noise of the towship gives a high Spearman's rank correlation coefficient.

Spearman's method of analysis is similar to that used in calculating Kendall's rank correlation coefficient because it deals with the ranks of the observations and not with the magnitudes of the measurements themselves. It is also a distribution-free (non-parametric) statistic and does not depend on any assumptions concerning the probability distribution of the values in either time-series.

To calculate Spearman's rank correlation coefficient, the observations in each set of beam-noise measurements must be replaced with their ranking relative to all other observations in that set (i.e., the measurements from beam 'j' are ranked separately from those of beam 'k'). The procedure used to rank each set of observations is identical to that described previously for Kendall's rank correlation coefficient and will not be repeated here. The ranks of corresponding positions in the two temporal sequences are then compared pair by pair (i.e., the rank of the first measurement in the time-series for beam 'j' is compared with the rank of the first measurement in the time-series for beam 'k'; this process is repeated for each of the N positions in the temporal sequences). Spearman's rank correlation coefficient is calculated by the following:

$$r_s = 1 - \frac{6 \sum_{j=1}^{j=N} d_j^2}{N(N^2 - 1)} ,$$

where:

d_j = the difference between the ranks of corresponding elements in the two temporal sequences.

Spearman's rank correlation coefficient (r_s) can have any value from +1 to -1. If the two series are identical, it is obvious that d_j will always be zero and that r_s will equal +1. Similarly, if one time-series is a mirror image of the other, it can be shown that r_s will always be equal to -1. Spearman's rank correlation coefficient can be used directly to identify data sets that appear to be strongly correlated. For example, data from two beams that are widely separated in space would be suspected of contamination if $r_s > r_{s\,max}$ (determined by level of confidence desired).

The coefficient may also be used as a test for significance, since the expected distribution of r_s is known to be symmetrical around the value 0, to approach the normal curve as N becomes large, and to be truncated at -1 and +1. Typically, the test for significance is applied to test the null hypothesis that the rank correlation coefficient in the population is zero, or we may say that the observations in the population are independent. Tables for r_s are available for small sample sizes (N<20) <5, 6>. For larger sample sizes the sampling distribution is close enough to normality that the normal area table may be used to find the probabilities. In this case the variance of r_s is given by:

$$\sigma^2_r = \frac{1}{N-1} .$$

As in previous tests, the observed coefficient (r_s) may be expressed in terms of the expected distribution $(0, \sigma_r^2)$ by the following:

$$ZSP = \frac{s}{\sigma_r} .$$

In conjunction with tabulated values for the normal distribution, the test statistic ZSP may be used to confirm or reject the independence hypothesis at any desired level of significance.

The correlation coefficients and their corresponding levels of significance (ZSP) are displayed in a rectangular matrix. Figure 3a is an example. The top row and left-hand column are beam numbers (the last two elements in each are for hydrophones). The elements above the main diagonal are the

SPEARMAN RANK CORRELATION COEFFICIENTS FREQUENCY 160 00
STANDARD DEVIATION CONVERSION FACTOR = 0640
ARRAY = MID
LEG 3 OF POLYGON 1 1/ 0/80 0 0 0
SAMPLES = 42

	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	65	66
22	64	87	58	39	37	-26	19	21	-14	34	16	-21	37	-45	25	-15	-28	-13	-18	-29	6	65	31
23	55	64	50	27	21	0	26	27	-3	31	0	-19	19	-29	11	-8	-20	-25	-25	-33	-4	50	19
24	37	32	64	33	10	-16	10	37	-13	25	30	-45	8	-10	-1	9	6	-12	-12	-14	-22	42	10
25	0	0	0	64	15	-51	15	-19	-7	30	31	-5	36	-22	48	-13	1	-2	19	7	42	42	26
26	0	0	0	0	64	-28	23	3	23	11	5	7	25	-38	65	-37	-17	0	-2	-8	49	26	3
27	0	0	0	0	0	64	-7	45	55	-3	-68	-16	-27	17	-25	-5	12	-33	-24	-4	-14	-24	-35
28	0	0	0	0	0	0	64	-20	19	9	32	-25	24	4	34	-19	7	-12	-3	-13	23	18	13
29	0	0	0	0	0	0	0	64	28	39	-24	-42	-3	4	-10	2	1	-22	-27	-14	-28	10	-21
30	0	0	0	0	0	35	0	0	64	-28	-42	-8	-4	-10	33	-8	16	-32	-6	7	39	-4	-24
31	0	0	0	0	0	0	0	0	0	64	4	-40	44	9	19	-25	3	-15	-9	-10	-1	25	17
32	0	0	0	0	0	0	0	0	0	0	64	-10	7	34	-5	9	-17	16	6	-13	-12	7	12
33	0	0	0	0	0	0	0	0	0	0	0	64	-10	-15	0	1	7	32	31	28	26	-6	-13
34	0	0	0	0	0	0	0	0	0	0	0	0	64	-17	47	-31	7	29	31	17	35	51	55
35	0	0	0	0	0	0	0	0	0	0	0	0	0	64	-46	33	7	0	3	7	-31	-36	-11
36	0	0	0	30	41	0	0	0	0	0	0	0	30	0	64	-42	11	11	37	32	80	54	30
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	64	36	-8	8	13	-27	-17	2
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	64	1	58	63	34	21	4
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	64	67	45	13	32	22
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	42	64	90	56	52	37
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	57	64	48	43	27
42	0	0	0	0	31	0	0	0	0	0	0	0	0	0	51	0	0	0	35	30	64	47	15
65	41	32	0	0	0	0	0	0	0	0	0	0	32	0	34	0	0	0	33	0	30	64	44
66	0	0	0	0	0	0	0	0	0	0	0	0	35	0	0	0	0	0	0	0	0	0	64

5.3 PERCENT OF BEAM COMBINATIONS CORRELATED WITH 99 73% CONFIDENCE

CORRELATION COEFFICIENT TIMES 100 IS ABOVE MAIN DIAGONAL
SIGNIFICANCE OF CORRELATION COEFFICIENT IN STANDARD DEVIATIONS TIMES 10 ON AND BELOW MAIN DIAGONAL
65 IS THE MEDIAN PHONE AND 66 IS A SINGLE PHONE, ALL OTHERS ARE BEAMS

FIG. 3a SPEARMAN'S RANK CORRELATION COEFFICIENT MATRIX FOR THE DATA OF ONE PERIOD OF THE SIMULATED MEASUREMENTS.
Correlation coefficients (x100) are above the main diagonal and the significance levels in standard deviations (x10) are on and below.

SPEARMAN RANK CORRELATION COEFFICIENTS
STANDARD DEVIATION CONVERSION FACTOR = .0693
ARRAY = HIGH
LEG 5 OF POLYGON 2 11/30/77 512:43
SAMPLES = 49

	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
3	100	25	-1	-4	0	-17	-22	-7	14	-9	-22	-16	-9	21	42	28	8	-2	-12	31	0	-3	17	-6	-4	-6	-17	-13	-7	6	-3
4	25	100	33	35	10	20	17	13	6	16	10	11	12	9	56	33	20	27	-3	-6	53	40	10	14	29	21	15	17	10	-18	15
5	-1	33	100	93	68	86	77	78	24	87	79	71	54	38	26	40	67	64	58	1	62	48	14	73	83	68	47	48	35	8	14
6	-4	35	93	100	58	87	86	83	26	83	82	73	61	42	24	37	70	69	66	4	71	63	28	59	87	81	58	63	44	8	14
7	0	10	68	58	100	72	58	62	25	54	54	56	48	35	2	27	39	44	46	5	41	28	11	66	52	40	32	30	19	7	-9
8	-17	20	86	87	72	100	92	82	8	80	87	81	64	37	5	24	58	63	66	-10	67	60	25	68	79	72	52	51	25	-6	4
9	-22	17	77	86	53	92	100	87	11	76	92	86	71	39	4	20	63	68	75	-6	60	71	19	53	83	81	65	62	33	-7	2
10	-7	13	78	83	62	82	87	100	42	73	85	81	63	47	14	30	68	70	79	12	54	61	25	59	89	87	74	71	53	14	11
11	14	6	24	26	25	8	11	42	100	20	18	24	22	30	15	30	25	15	28	40	9	12	24	22	32	33	27	26	31	21	-10
12	-9	16	87	83	54	80	76	75	20	100	89	82	64	36	21	34	68	66	64	0	54	48	12	57	79	72	56	56	36	12	-1
13	-22	10	79	82	54	87	92	85	18	89	100	94	74	43	9	23	67	70	78	-10	51	66	17	57	83	80	70	65	40	7	-4
14	-16	11	71	73	56	81	86	81	24	82	94	100	87	54	5	22	60	68	77	-3	54	67	23	55	76	75	65	58	32	7	-12
15	-9	12	54	61	48	64	71	63	22	64	74	87	100	66	2	24	55	68	77	5	39	67	32	44	65	69	62	56	36	12	-16
16	21	9	38	42	35	37	39	47	30	36	43	54	66	100	7	17	42	52	61	14	35	40	24	27	41	39	31	34	29	27	-13
17	42	56	26	24	2	5	4	14	15	21	9	5	2	7	100	72	46	30	7	9	29	20	-13	6	21	17	13	15	30	23	31
18	28	33	40	37	27	24	20	30	30	34	23	22	24	17	72	100	64	46	36	11	37	18	3	30	33	33	27	27	33	14	20
19	8	20	67	70	39	58	63	68	25	68	67	60	55	42	46	64	100	82	68	16	55	51	6	41	66	66	37	59	53	16	14
20	-2	27	64	69	44	63	68	70	15	66	70	68	68	52	30	46	82	100	81	20	74	63	21	45	72	73	70	68	52	11	24
21	-12	-3	58	66	46	66	75	79	28	64	78	77	77	61	7	36	68	81	100	13	53	59	30	47	71	79	78	77	55	14	6
22	31	-6	1	4	5	-10	-6	12	40	0	-10	-3	5	14	9	11	16	20	13	100	15	14	26	-5	5	4	5	1	10	16	6
23	0	53	62	71	41	67	60	54	9	54	51	54	59	35	29	37	55	74	53	15	100	73	44	44	63	62	50	48	28	-3	24
24	-3	40	48	63	28	60	71	61	12	48	66	67	67	40	20	18	51	63	59	14	73	100	46	30	66	64	66	55	32	10	3
25	17	10	14	28	11	25	19	25	24	12	17	23	32	24	-13	3	6	21	30	26	44	46	100	21	30	37	29	22	7	2	6
26	-6	14	73	59	66	68	53	59	22	57	57	55	44	27	6	30	41	45	47	-5	44	30	21	100	69	43	33	20	10	6	0
27	-4	29	83	87	52	79	83	89	32	79	83	76	65	41	21	33	66	72	71	5	63	66	30	69	100	89	74	66	48	8	16
28	-6	21	68	81	40	72	81	87	33	72	80	75	69	39	17	33	66	73	79	4	62	64	37	43	89	100	87	84	58	2	19
29	-17	15	47	58	32	52	65	74	27	56	70	65	62	31	13	27	57	70	78	5	50	66	29	33	74	87	100	90	63	11	12
30	-13	17	48	63	30	51	62	71	26	56	65	58	56	34	15	27	59	68	77	1	48	56	22	20	66	84	90	100	80	18	23
31	-7	10	35	44	19	25	33	53	31	36	40	32	36	29	30	33	53	52	55	10	28	32	7	10	48	58	63	80	100	51	37
32	6	-18	8	8	7	-6	-7	14	21	12	7	7	12	27	23	14	16	11	14	16	-3	10	2	6	8	2	11	18	51	100	17
33	-3	15	14	14	-9	4	2	11	-10	-1	-4	-12	-16	-15	31	20	14	24	6	6	24	3	6	0	16	19	12	23	37	17	100
34	-7	36	59	61	22	49	45	57	20	49	45	36	25	8	45	38	51	55	39	24	62	49	24	39	64	57	50	49	54	27	63
35	0	39	67	71	27	59	56	66	25	62	57	49	38	23	47	41	58	63	49	27	67	61	28	41	71	63	53	55	58	31	47
36	5	42	71	75	29	63	62	70	24	66	62	53	44	36	50	45	69	69	58	22	63	57	19	37	69	63	49	59	64	26	42
37	17	38	70	69	42	62	57	69	40	68	63	61	49	42	50	45	61	62	58	28	53	50	24	45	63	57	43	49	51	22	24
38	27	10	34	29	39	20	14	32	45	30	19	20	13	16	23	17	19	16	13	43	10	5	13	29	27	15	6	5	18	19	16
39	6	45	-9	7	-17	-12	6	2	10	-22	-15	-16	-2	-4	26	17	7	8	-1	17	18	28	3	-19	5	9	7	12	18	9	17
40	51	37	-21	-28	-12	-31	-26	-17	16	-28	-30	-20	-11	7	15	7	-19	-21	-23	6	-16	-8	-4	-14	-14	-20	-19	-19	-10	-8	-16

FIG. 3b SPEARMAN'S RANK CORRELATION COEFFICIENT MATRIX FOR DATA MEASURED BY A TOWED ARRAY DURING ROUGH SEAS.
Coefficients greater than 0.49 have been circled.

correlation coefficients (×100, for display purposes) and those on and below are the confidence levels in standard deviations (×10, also for display purposes). To facilitate picking out possible problem areas, all significance levels less than three standard deviations (30 in the matrix) have been replaced by zeroes. The remaining elements indicate that the hypothesis of independence can be rejected with a confidence level of greater than or equal to 99.73%.

Figure 3a corresponds to the measurement of noise in a "well-behaved" (simulated) noise field by a perfect (simulated) array. As a result, the correlation matrix is rather uninteresting. Figure 3b, on the other hand, was generated from actual towed-array data measured during a period of extremely rough seas. Only the Spearman's rank correlation coefficient appears in the matrix; the significance level was added to the software later. The coefficients exceeding 0.5 (50 in the matrix) have been circled. This corresponds to significance levels greater than or equal to 99.96%. Hence, the hypothesis that the beam-noise outputs are uncorrelated can be rejected and the alternate hypothesis that they are correlated can be accepted with a very high level of confidence (99.96%). Post-analysis of the data indicated that side-lobe suppression was as little as 3 dB. This was probably a result of the extremely rough seas distorting the shape of the array.

2.8 Beam Polar Plots of the Median Noise Level

The median level for each beam-noise time-series is obtained and displayed as in Fig. 2, col. 8. Tabular format, however, is not conducive to instant recognition of possible problems. For this reason a polar plot of these data is provided when it is required to estimate the noise-field directionality. Figure 4a is a typical example from the simulated noise measurements. The sources of noise along endfire (towship) and broadside (stationary source) are readily apparent. However, the utility of this display for spotting problems is more apparent in the actual measured data of Fig. 4b. Two cases are shown here; two sets of data illustrate each case. The beam-noise patterns on the left-hand side are for periods when a towed array was operating very well. The large beam-to-beam contrast, especially in the relative direction of the towship (about 45°R), is evidence of the excellent system performance. The patterns on the right-hand side were measured at the same location about a month later. At that time the seas were extremely rough and the array had to be retrieved to prevent losing it. The lack of beam-to-beam variability in these plots suggests poor beamforming, since the towship is normally equivalent to a high-level stationary source. This is the same measurement period during which the data for the Spearman's rank correlation matrix in Fig. 3b were collected and during which post-analysis indicated sidelobe suppression levels as low as 3 dB. These results do not "pinpoint" the source of a problem but they can clearly indicate the existence of one.

3 ANALYSIS PRODUCTS

The utility of a particular statistical parameter or product in the analysis phase of an exercise is determined both by the objectives of the exercise and the imagination of the analyst. Several products are listed

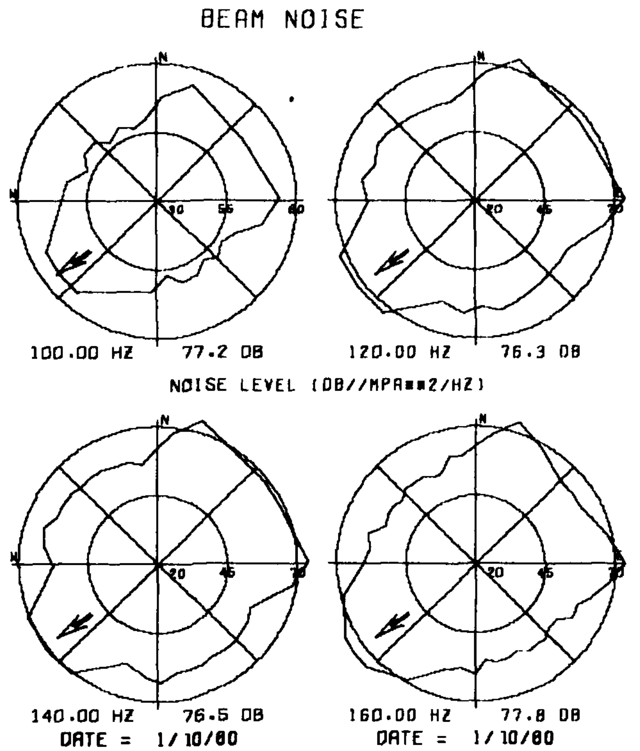

FIG. 4a EXAMPLE BEAM NOISE PLOT OF MEDIAN BEAM NOISE LEVELS OBTAINED FOR THE THIRD PERIOD OF THE SIMULATED MEASUREMENTS.
Noise sources are at 090°(E) and forward endfire (about 220°).

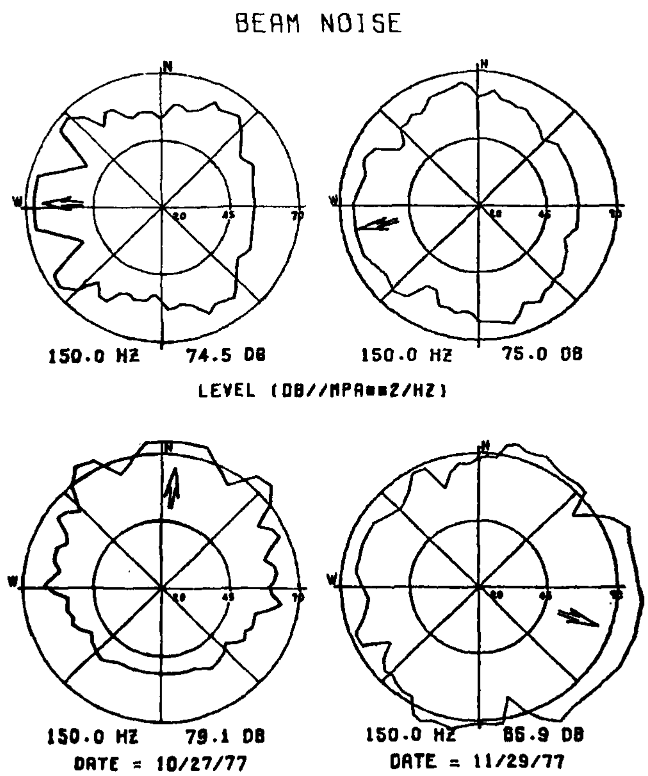

FIG. 4b BEAM NOISE PLOTS FOR TIME PERIODS WHEN THE SEAS WERE MODERATE AND THE ARRAY PERFORMANCE WAS GOOD (LEFT-HAND SIDE) AND WHEN SEAS WERE ROUGH AND THE PERFORMANCE WAS POOR (RIGHT-HAND SIDE).

below and discussed in the indicated Sections of this Chapter. Some are sufficiently general to have nearly universal application, while others, in their present form, are applicable only to line-array data; it will be pointed out when the latter applies.

- Beam-noise statistics (see Sect. 3.1):
    1) 10, 25, 50 (median), 75, and 90 percentiles,
    2) Geometric mean intensity level (decibel average) and average power levels,
    3) Standard deviation, skew and kurtosis, see Sect. 3.3.

- Plots of the cumulative distribution function (see Sect. 3.2):
    1) beam noise
    2) phone noise
    3) array-noise gain

- Plots of the azimuthal anisotropy cumulative distribution function (AACDF) (cumulative distribution functions as a function of beamwidth, line array only), see Sect. 3.3.

- Median noise-field directionality estimate/beam response deconvolution, see Sect. 3.4.

- Estimates of the 50 (median), 25, and 10 percentile noise field directionalities, see Sect. 3.5.

- Auto- and cross-correlation, see Sect. 3.6

- Kolmogorov-Smirnov test for log-normality, see Sect. 3.7.

The above products are illustrated and discussed in the context of ambient-noise measurements using a towed array. However, the only restriction on the data is that they be in the form of time-series of complex coefficients. The type of data and the measurement system are arbitrary.

3.1 Beam-noise Statistics

The following basic statistics of each beam-noise time-series provide some indication regarding the distribution function for the data sets:

a) 10, 25, 50 (median), 75, and 90 percentiles (Fig. 2, cols. 6 to 10)

b) geometric mean intensity levels (decibel average) and average power levels (Fig. 2, cols. 11, 12)

c) standard deviation, skew (related to the third moment), and kurtosis (related to the fourth moment) (Fig. 2, cols. 13 to 15).

3.2 Plots of the Cumulative Distribution Function (CDF) (Fig. 5)

These summaries of noise levels illustrate the temporal variability in the directional noise fields and complement the horizontal directionality

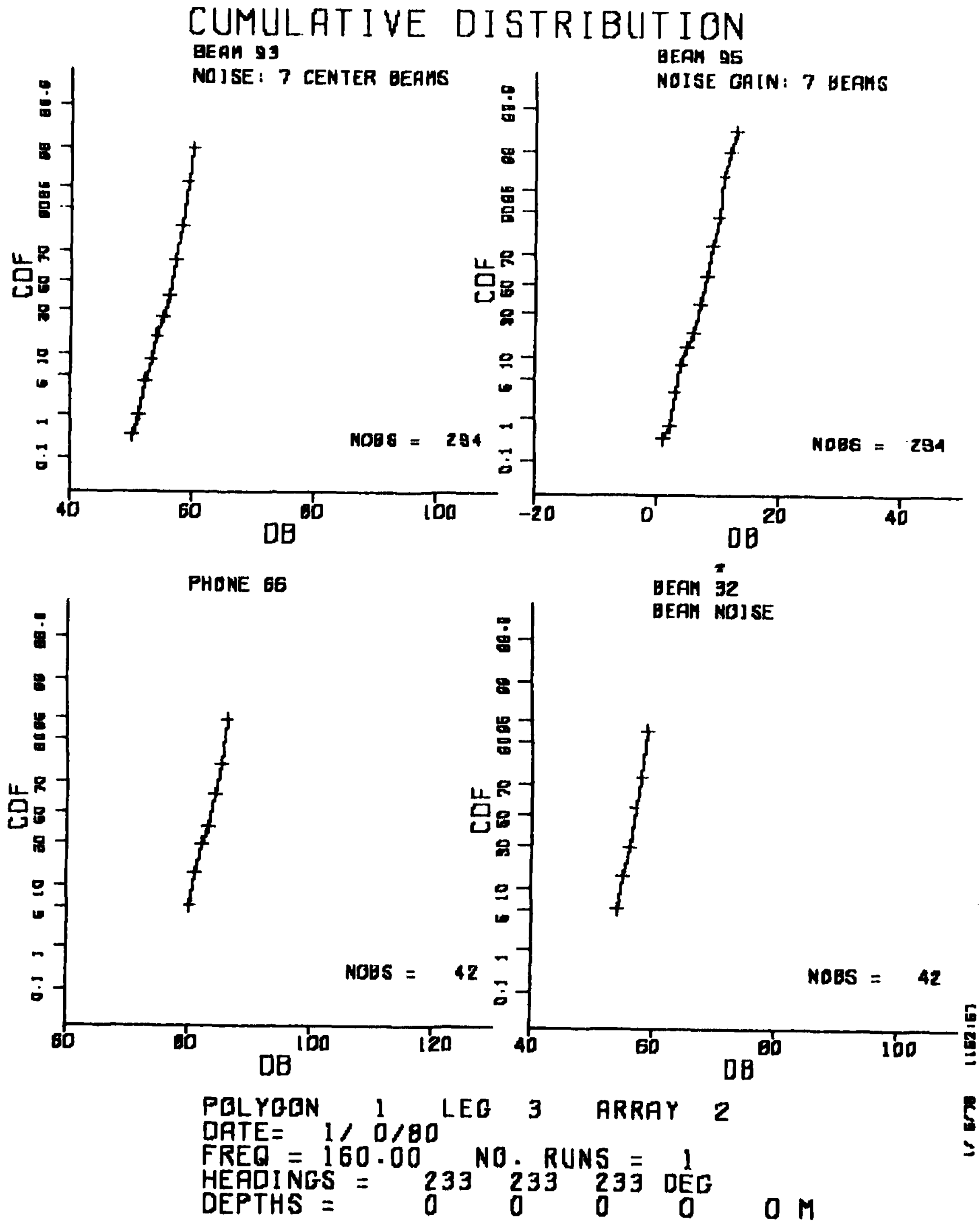

FIG. 5 CUMULATIVE DISTRIBUTION FUNCTION PLOTS OF BEAM NOISE, HYDROPHONE NOISE, AND BEAM NOISE GAIN FOR THE THIRD PERIOD OF SIMULATED MEASUREMENTS.

patterns. Cumulative distribution plots of the noise levels and gains for various beams or azimuthal sectors specify the occurrence and magnitude of the ambient-noise levels and indicate times and azimuths conducive (or adverse) to the detection process. CDF plots of the following are obtained:

a) beam-noise levels,
b) hydrophone-noise levels,
c) array-noise gain.

In addition, the data can be accumulated over many measurement periods (i.e. an entire noise polygon) and displayed as in Fig. 5.

3.3 Plots of the Azimuthal Anisotropy Cumulative Distribution Function (AACDF) (Fig. 6)

The polar plots of beam noise in Fig. 4 illustrate the influence of the spatial variability of the noise field on the beam noise of the array. These results, however, are the median levels for a single measurement period, for a single array heading, and for the acoustical response characteristics (i.e. beam patterns) of the measurement array. They have considerable utility in the assessment of data quality but very little in analysis. The same data, however, can be very useful when utilized in a slightly different manner. The first step is to deconvolve the beam-pattern response from the beam levels to produce an estimate of the noise field folded about the array axis. This is automatically accomplished by the noise-field directionality estimation algorithm <7> when the beam data from only one measurement period are input. The deconvolved noise field within 120° or less of broadside is then passed through a sin X/X filter to obtain cumulative distribution functions as a function of filter width. The filter width is increased in ½° steps from ½° to 10°. Since the ambiguity is not resolved, the filter output corresponds to the conical beam output of a line-array having the same beamwidth as the filter width. Hence the output of the filter is a measure of the azimuthal anisotropy that would be observed by an array having the same beamwidth - thus the name "azimuthal anisotropy cumulative distribution functions".

If it is assumed that the noise coherence experienced by a different array is approximately the same as for the array that took the data, the filtered results are good extrapolations for other arrays having different beamwidths. Repeating the deconvolution and filtering procedure with additional data sets, and accumulating the results, yields cumulative distribution functions for beamwidths from ½° to 10°. These functions are plotted horizontally and stacked vertically with increasing beamwidth. Lines are then drawn across them to connect equal levels, resulting in plots such as Fig. 6.

A cut through Fig. 6 along a horizontal line (parallel to the abscissa) gives the beam-noise cumulative distribution function for a line array that has a beamwidth equal to the value at the location (on the ordinate) at which the cut was made. For example, the results in Fig. 6 indicate that for an array having a beamwidth of 4°, 40% of the azimuthal space will yield beam levels less than 52 dB for the particular orientation of the array and 80% of the azimuthal space will yield levels that are less than

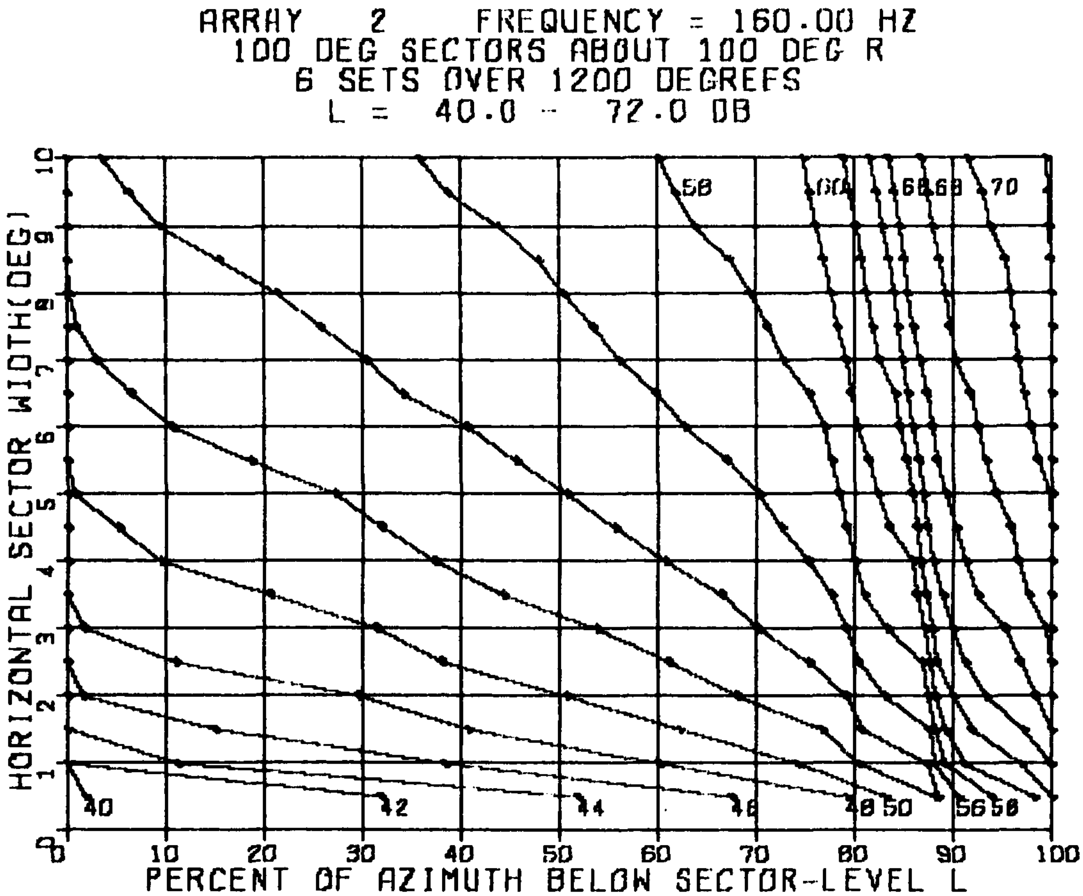

FIG. 6 AZIMUTHAL ANISOTROPY CUMULATIVE DISTRIBUTION FUNCTION (AACDF) PLOT FOR THE SIMULATED MEASUREMENTS

58 dB. For an array having a beamwidth of 1°, the corresponding levels would be 46 dB and 52 dB respectively. Six decibels difference in the beam noise for the two arrays is to be expected, since the noise field, from which Fig. 6 was generated, consisted mostly of white noise and ten times the log of the beamwidth ratio (4) is 6 dB.

Plots similar to Fig. 6 are used to find the expected distribution of beam-noise levels for a given beamwidth and array heading. When the data are collected on many different headings the results apply to more general scenarios of arbitrary array heading. The latter form is often more useful in system-performance studies when the location of the target and the array orientation are random variables.

An additional feature of the AACDF, worth mentioning, is that a plot can be generated for any desired sector. For example, the results for a beam in the sector from 350° true clockwise to 090° true can easily be obtained.

3.4 Median Noise-Field Directionality Estimate/Beam Response Deconvolution

Horizontal directionality is an important statistic of the ambient noise field. Figure 7 illustrates the directionality estimates resulting from the simulated measurements by an ideal towed array in a noise field consisting of two sources in a background of "white noise". One source was at 090° true throughout the six different data-measurement periods. The other source was always at 000° relative (forward endfire), to simulate the towship.

The algorithm used to generate the noise directionality estimates (WIT) is discussed in <7> and contains the corrections for array tilt, three-dimensional beam-response patterns, and noise-field vertical-arrival structure discussed in <8>. It is also possible to eliminate contaminated beam data from the directional estimation process by instructing the program to skip those beams.

The basic WIT technique involves deconvolving the beam responses from the median beam-noise level data to get an estimate of the true noise field and then convolving the estimate with the beam patterns to get back to the measured result. The differences between before and after are used to modify the estimate of the noise field. This is done a little at a time and iterated over and over again until no further improvement results. The standard deviation of the differences is used to judge the non-stationarity of the field and how representative the estimate is of the actual field. For example, the standard deviation associated with the estimated directionality of a stationary field is generally a fraction of a decibel (usually less than 0.3 dB). A larger value can be attributed to the non-stationarity of the field (i.e. transitting of ships). As the standard deviation decreases, the array loses its ability to distinguish the noise-field estimate from the real noise field. A standard deviation of zero does not imply that the two are identical, just that the array can not tell the difference.

Including the three-dimensional characteristics of the array and the vertical arrival structure of the noise field in the estimation process requires *a priori* knowledge of the shape of the latter. This can be

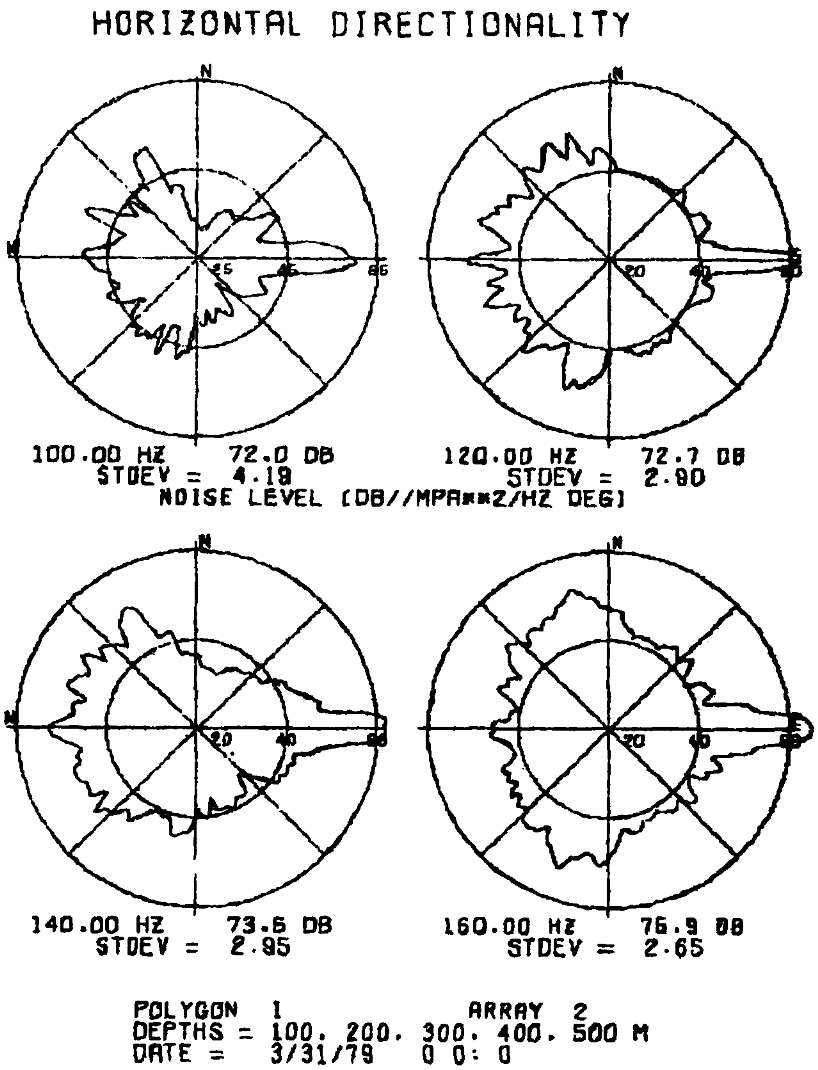

FIG. 7 ESTIMATE OF THE MEDIAN HORIZONTAL DIRECTIONALITY OF THE SIMULATED NOISE FIELD.
A source was always at 090° true during the measurements and one of equal level along forward endfire (towship at 000°R).

obtained from historical data, concurrent measurements by a vertical array, or an educated guess. The latter is not too unrealistic, since the shape of the vertical pattern is determined more by the propagation conditions at the measurement depth (i.e. in or out of a channel, bottom-limited propagation) than by the spatial distribution of the sources. This is not so for the horizontal directionality of the noise. When the vertical dimension is included, the shape of the vertical pattern should be presented with the horizontal directionality estimates. The technique for estimating noise directionality <7> is independent of the manoeuvres during which the data are taken. The only requirement is that at least two sets of data must be acquired while the array is on different headings for the ambiguities to be resolved. Hence the towship could tow the array in a polygon pattern, as is commonly done with a long array, or it could tow it in a circle, which is possible with a short array <9>.

WIT deconvolves the beam response from the data. Hence the technique could be used for any application that benefits from deconvolution, such as analysis of vertical array data or the improvement of bearing estimation in horizontal line-array data.

The utility of the directionality pattern (as in Fig. 7) results from it being an estimate of the unambiguous noise-field directionality, independent (within reason) of the measurement tool. When the beam patterns of an arbitrary array (linear, planar, spherical, etc.) are convolved with the directionality pattern, an estimate of the median beam-noise level is obtained.

3.5 Estimates of the 50 (median), 25, and 10 Percentile Noise-Field Directionalities

The temporal variability of the noise as a function of beam number for 10, 25, 50, 75, and 90 percentiles are obtained and tabulated in Fig. 2, cols. 6 to 10. Unfortunately, for a horizontal line-array these are ambiguous in azimuth angle.

However, there is an interesting property of the array noise-response that can be utilized to aid in the directionality estimation. Noise from a high-level soruce generally comes from only one direction. If it is not at the same location while the array is making a measurement on a different heading, its direction can not be resolved. This is generally the case with noise due to near, or moderately near, shipping. Low-level noise, on the other hand, is immediately resolvable. The noise must be at least that low in both ambiguous directions; otherwise a low value could not have been measured. By using this property of the array response to the noise field and the Simple Mean Ambiguity Resolution Technique (SMART) <10>, estimates of the 10 and 25 percentile directionality patterns can be obtained. These can then be plotted with the 50 percentile (median) pattern, obtained as previously discussed, to indicate the 10, 25, and 50 percentile temporal statistics as a function of azimuth. Figure 8 illustrates an example for the simulated noise-field.

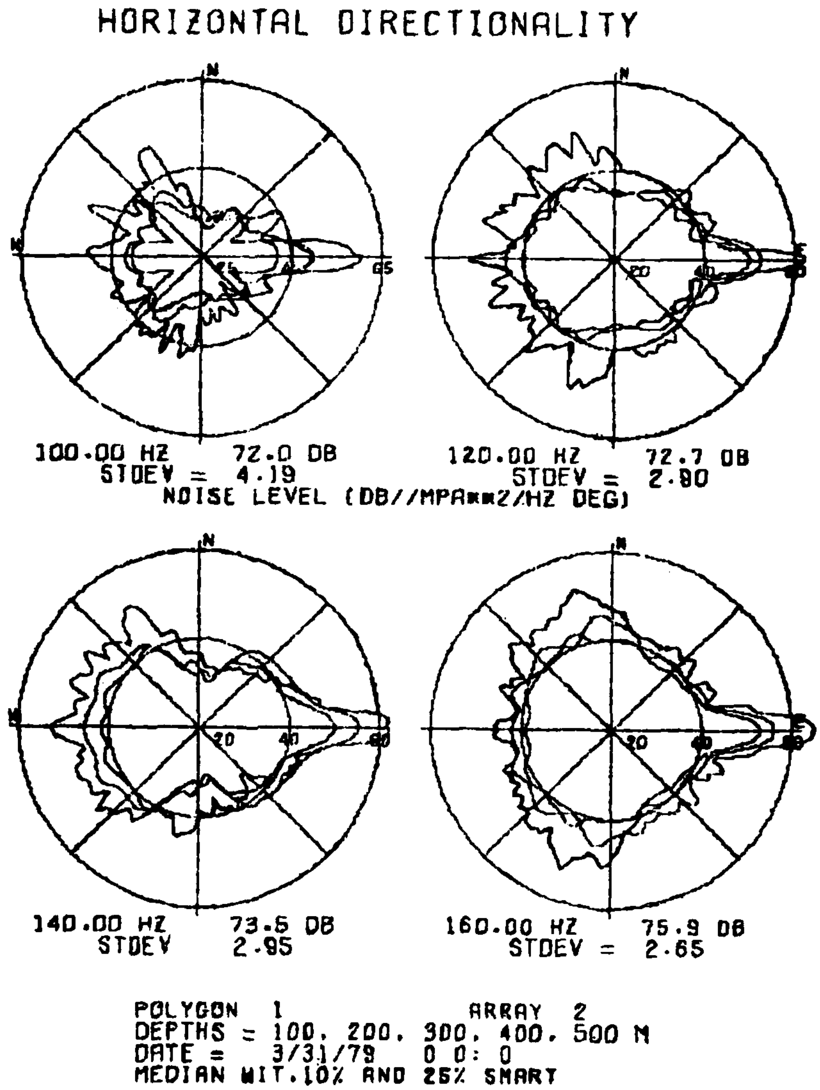

FIG. 8 ESTIMATES OF THE 10, 25, AND 50 (MEDIAN) PERCENTILES OF THE NOISE AS A FUNCTION OF AZIMUTH.
The 50 percentile curve is identical to Fig. 7.

3.6 Auto- and Cross-correlation

Auto- and cross-correlation of sets of time-series data are at present possible with the onboard system. This option, however, is used only to address specific questions that are generally unique to a given data set.

3.7 Kolmogorov-Smirnov Test for Log-normality

The Kolmogorov-Smirnov (KS) test for log-normality <11> compares the normalized cumulative distribution function of beam-noise levels with an expected cumulative distribution function of a log-normal population. The largest difference is checked to see if it is within a certain limit, which depends on sample size. If it does, then the hypothesis that the data are log-normal distributed cannot be rejected. Unfortunately, the lowest values of beam-noise data are controlled by the sidelobe suppression capability of the array. Poor sidelobe suppression will bias the low levels to higher values without appreciably affecting the high values. Under such conditions, beam-noise from sectors in which the noise levels are log-normal distributed would fail the KS test. This would not be a problem for a beam that consistently measured relatively high levels.

The utility of the KS test could be increased by excluding the lowest levels in the distribution. This is easily justified if the test is to determine a property of the noise-field rather than the array output. This, however, is not done at present.

CONCLUSION

The software for on-board processing of acoustic data has been demonstrated to be useful for assessing data quality and to possess several products that help define the statistical characteristics of the noise field. Although some techniques in the present implementation are restricted to line-array data, the majority are completely general. This software is at present operational on SACLANTCEN's Hewlett Packard real-time processing mini-computers and can be made available to whoever needs such analyses.

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APPENDIX A

IMPLEMENTATION ON AN HP 21MX COMPUTER

A.1 Overview

The purpose of this appendix is to provide basic user documentation for the beam-noise data processing and reduction system implemented on an HP 21MX computer. Included herein are descriptions of the logical flow of the WIT technique and each subroutine. In addition, the system outputs are described and illustrated by meaningful examples, relating the output products to the user. The ambient-noise data collection programs provide the inputs to WIT and perform the following functions on the beam and hydrophone noise time series:

a. Data quality assessment

   (1) Number of Runs Test
   (2) Mean Squared Successive Difference Test
   (3) Kendall's Test for Correlation
   (4) Spearman's Rank Correlation Coefficient

b. Calculation of beam-noise and phone-noise temporal statistics

   (1) 10, 25, median (50), 75, and 90 percentile values
   (2) Decibel average, power average, and the standard deviation, skew, and kurtosis of the beam and phone decibel time series
   (3) Cumulative distribution functions of beam noise, phone noise, and noise gain

c. Spatial statistics

   (1) Noise field horizontal directionality (from WIT)
   (2) Azimuthal Anisotropy Cumulative Distribution Functions (AACDF) (from WIT)

The input data for the processing program are written on magnetic tape by a beamformer and manually transferred to the batch processor. The tape contains the beam complex coefficient data resulting from the double FFT beamforming. The median values for each time period (leg) are written to a file ($NOISE) that is the input for WIT.

A.2 Logic Flow Diagram of Iterative Technique

Figure A.1 illustrates the flow of logic required to calculate the estimated horizontal directionality of noise from outputs of a towed array. The process involves the analysis of data collected from an array towed in a polygon pattern. No data are collected while the tow ship is turned to the next leg of the polygon. Once the data are collected, the program can be run. The program is comprised of four main programs and a number of subprograms, subroutines, and functions as shown in Table A.1; when the programs are linked together they achieve the desired result, which is the calculation of horizontal directionality.

A.3 Program and Subroutine Descriptions

Table A.1 contains an overview of the relationships between the programs used. The four main programs call subroutines that are both internal and external. The table attempts to indicate this so that the programmer seeking a particular listing will know where to look. Note: Some internal subroutines are used in more than one external subroutine.

A.4 Major Noise Program Segments

The Towed-Array Noise Analysis Program consists of the following major segments:

a. RDLMA

RDLMA selectively reads data from a beamformer tape. The data are formatted in a data file (INSTAT), which is used by the NSTAT program.

b. NSTAT

NSTAT processes the data and prints the output in a readable format. During processing, if the option has been selected, the program prepares a data file (SCDFST) for use by the Cumulative Distributed Function program.

c. CDFPL

CDFPL plots the data stored in the data file (SCDFST).

d. NOISE

NOISE is a noise-ambiguity resolution program that determines the ambient-noise level and the direction from which the noise is coming. The input data for this program were prepared by the NSTAT program and written in the $NOISE file. As part of the output for this program a data file ($AMDAT) is prepared for use by the Field Plot program.

e. NOIS7

NOIS7 is a noise-field directionality plot program that plots the results of the NOISE program.

A.4.1 RDLMA Subprogram and Routines

Subprogram R3LMA selectively reads data from a beamformer tape. The data are formatted in the data file (SNSTAT). The program asks for the following inputs:

a. Frequencies
b. Hydrophone
c. Tape start-time
d. Tape stop-time
e. Array type
f. Polygon and leg number
g. Nonacoustic data

Subprogram R1LMA provides dimension and equivalence of data from the output of the beamformer.

Subroutine CKTIM checks current time against time boundaries and signals the acception or rejection of data. If tape is after stop time, the routine asks for a new start and stop. If the start-time hour is less than zero, the program is terminated.

Subroutine BLOCK stores data.

Subprogram R2LMA, on first data set, build $STAT file.

Subroutine DFDTA sets up NSTAT data-define records for RDLMA.

Function WEIGT computes inverse Hann for NUM phones.

Subroutine DDNAD gets inputs or use default values.

Function FINTP interpolates, in log frequency, the points of the transfer function of the system SCHs through the beamformer.

Function FRESP calculates the filter response part of the system transfer function.

Function FERR processes error returns from FMP program calls.

A.4.2 Program NSTAT Subprogram and Routines

NSTAT calculates noise statistics of raw data and provides links to subprograms STAT2, STAT3, STAT4, STAT5, STAT6, and STAT7.

Subroutine GETFR retrieves data that have been pre-stored into data file by program RDLMA by date and time (along with other basic variables) for selected frequencies.

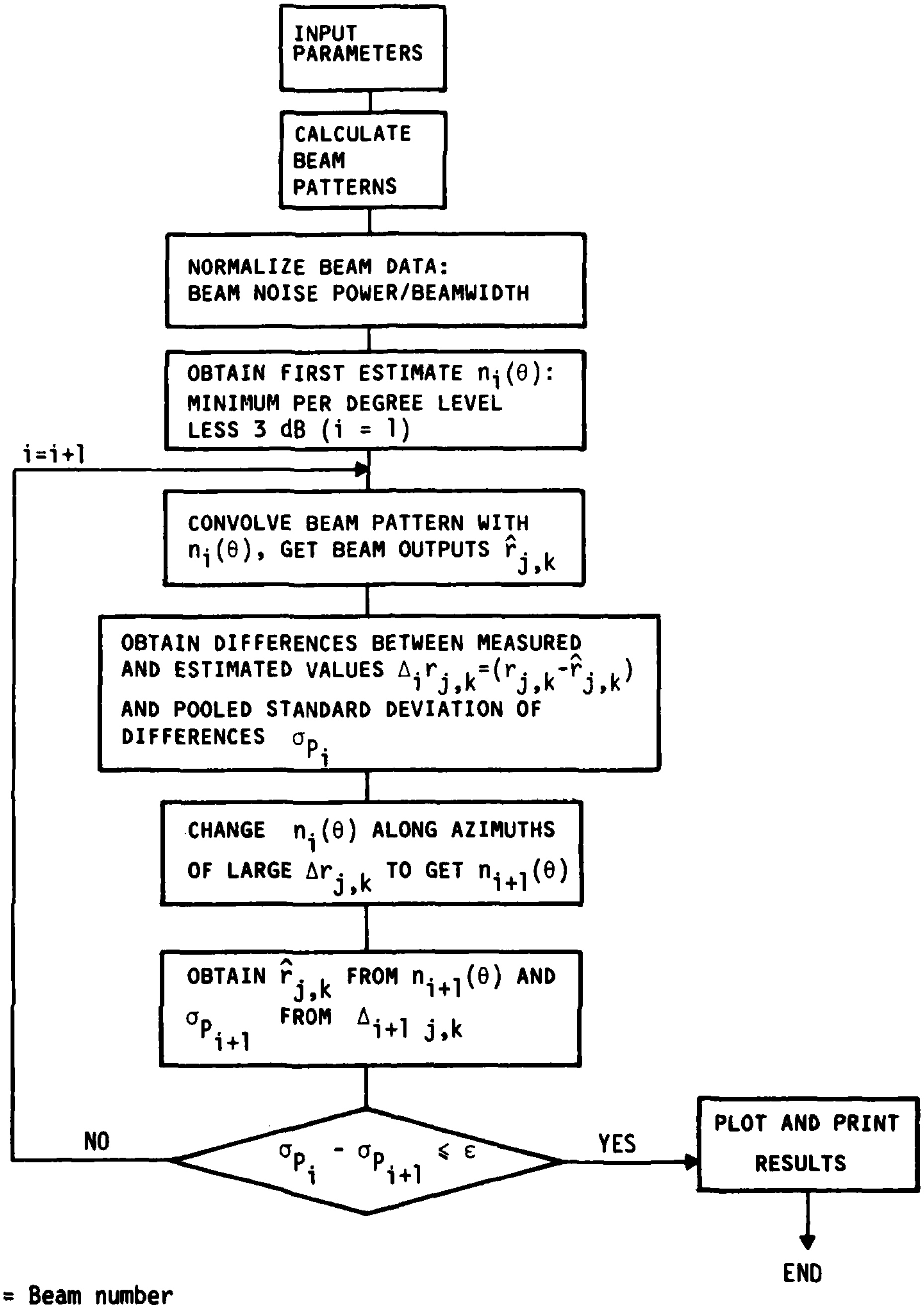
Subprogram STAT2 performs the regular statistics on noise data including: median, average, standard deviation, skew, and kurtosis. If leg number is not 99, it dumps median data to the $NOISE file for use by the noise ambiguity resolution program.

Subroutine BHDX calculates the beam numbers of the usable beams.

Subroutine SZTAU computes various percentiles.

Subroutine CLOZE finds the index of the element closest to the given ranked position.

Subroutine JRANK places the rank of an integer vector in another integer vector. The original vector is left unchanged. In case of ties, the average of the ranks is assigned.



<u>NOTE</u>:
j = Beam number
k = Array heading number
i = Iteration number

FIG. A.1 WIT LOGICAL FLOW BLOCK DIAGRAM

TABLE A.1

RELATIONSHIPS BETWEEN WIT PROGRAMS

PROGRAM	SUBPROGRAM	INTERNAL SUBROUTINE	EXTERNAL SUBROUTINE	FUNCTION
RDLMA				
	R3LMA			FERR
	R1LMA	CKTIM		
		BLOCK		
	R2LMA		DFDTA	FERR
			DDNAD	WEIGT
				FINTP
				FRESP
NSTAT		NWPAG	GETFR	
	STAT2	NWPAG	BHDX	
			SZTAU	
			CLOZE*	
			JRANK*	
	STAT3	GROUP	QSORT	FNORM
	STAT4	RDBEM		
		CORLT		
	STAT5	RDBEM	BHDX	
		JRANK		
	STAT7			
	STAT6	GROUP	QSORT	
			BHDX	
				FDIST
NOISE	PROB	SETUP		
		PROBL		
			AXIS	
	NOIS1		ASIN(X)	FERR
			BWCAL	
			SMART	
	NOIS5	MSQD	RESP	
		CONV		
	NOIS2	MSQD		
		CONV		
	NOIS6			
		RFTMA		
NOIS7				

APPENDIX B

SIMPLIFIED EXAMPLE OF A RUN PROCEDURE

B.1 Run Procedure

The beam-noise data-processing programs can be run easily on the batch computer. The following example illustrates this and can be used as a guide if the operator responses are modified to reflect the parameters that characterize the type of processing desired.

In the following run example the instructions in brackets are those entered by the operator. These always end in the symbol R for RETURN. The statements or character sequences not bracketed appear automatically on the CRT to indicate program status or to solicit the appropriate response. To analyze noise data the following interaction between the operator and computer takes place:

1. The operator mounts the beamformer output tape that contains beam complex coefficient data on the tape transport of the batch computer.
2. The operator enters the file-manager mode of the computer [indicated by the colon (:)] and starts the noise-analysis program by typing :*INSTH::25,1,R
3. The following interaction takes place:

```
ARRAY TO PROCESS (1 = LOW, 2 = MID, 3 = HIGH)
[3, R]
INPUT 5 FREQUENCIES (OR TYPE 'STANDARD')
[50,100,148,48,R]
INPUT 1 PHONE TO PROCESS
[8,R]
INPUT TAPE START TIME (HR, MIN, SEC)
[0,0,0,R]
INPUT TAPE STOP TIME (HR, MIN, SEC)
[0,31,0,R]
ENTER NUMBER OF POINTS TO AVERAGE
[1,R]
ENTER NUMBER OF BAD PHONES
[25,R]
ENTER TIME WEIGHT (1=UNIFORM, 2=HANN, 3=HAMM)
[2,R]
```

```
ENTER SPATIAL WEIGHT (1=UNIFORM, 2=HANN, 3=HAMM)
[1,R]
SAMPLING FREQUENCY = 5000 Hz
FFT LENGTH = 2048
ENTER NUMBER OF ACQUIRED BANDS (FROM 1 TO 8) OR TYPE Ø FOR STANDARD
[Ø,R]
HYDROPHONE SENSITIVITY SET TO -145.0 DB
IS THIS A LONG STAT RUN?
[NO R]
IF DATA O.K. TYPE 1
[1,R]
TIME IS 0:0:5
INPUT POLYGON   AND LEG:  (POLY, LEG):
[1,1,R]
ENTER SOUND SPEED:
[1500,R]
... NADS PARAMETERS ...
SCU= -
HEADINGS = - - - - -
DEPTHS = - - - - -
JULIAN DAY = -
LATITUDE = -DEG -MIN
LONGITUDE = -DEG -MIN
DO YOU WISH TO USE THESE VALUES??
[NO R]
ENTER SCU GAIN
[36, R]
ENTER 3 ARRAY HEADINGS (EX. 39,42,50,):
[225,224,0, R]
ENTER JULIAN DAY:
[163, R]
ENTER 5 DEPTHS IN METERS (EX. 220,232,255,270):
[757,881,881,0,0, R]
ENTER LATITUDE (DEG,MINS,SEC,):
[23,04,0, R]
```

```
ENTER LONGITUDE (DEG,MIN,SEC,):
[91,29,0, R]
TIME IS 0:1:4
 "      0:2:4
 "      0:3:3
 "
 0
 0
 0
END OF DATA !!! DO YOU WISH TO CONTINUE?
[NO R]
DO YOU WITH TO SEE THE HYDROPHONE PLOT?
[YES R]
RDLMA : STOP 0000
1
** END STATS **
PLOTS REQUESTED:
1 3 4 11 12 14 16 22 23 25 27 33 34 36 38 44
ENTER LEG NUMBER:
[1, R]
::
LEG > 1 ← MOUNT TAPE FOR LEG 2, etc.
[:*STATH:25,1, R]

                        SAME AS AFTER
                        :[*INSTH::25,1, R]
                        REPEAT FOR N LEGS

[:RU,CDFPL,1,2, R]
PLOTS REQUESTED
1 3 5 11 12 14 16 22 23 25 27 33 34 36 38 44 45 47 49 55
[:RU,NOISE, R]
HOW MANY FREQUENCIES?
[5, R]
HOW MANY LEGS?
[6, R]
```

```
HANN OR UNIFORM SPATIAL SHADING? (HA OR UN):
[UN R]
DO YOU WANT AACDF PLOTS?
[YES R]
IF YOU WANT SECTOR REL TO NORTH, INPUT CENTER, WIDTH
IF NOT, INPUT 0,0,RETURN
[0,0, R]
IF YOU WANT SECTOR REL TO ARRAY OTHER THAN STANDARD, INPUT
    CENTER, WIDTH
IF NOT INPUT 0,0,RETURN.
[0,0, R]
NOISE:  STOP 0000
[:RU,NOIS7 R ]
PLOT GENERATED → NOISE DIR & BEAM-NOISE PLOTS
```

A typical set of output from such a run is included in the main text as Figs. 1 to 8.

B.2 Compile, Load, and Run Procedures

The noise programs should not have to be compiled, because they are available on disk in a compiled form. However, if modification of any part of the programs should be necessary, the following compile procedures are available.

The easiest method for compiling and listing all the programs is to execute the following instruction:

```
:*NLST
```

If for some reason *NLST is not available on the disk, each segment will have to be compiled using the following instructions:

RDLMA

```
• : RU, FTN4, &RDLMA :: 25, 6,,,L
• : RU, FTN4, &R1LMA :: 25, 6,,,L
• : RU, FTN4, &R3LMA :: 25, 6,,,L
• : RU, FTN4, &DDNAD :: 25, 6,,,L
• : RG, FTN4, &SMSEG :: 25, 6,,,L
```

```
NSTAT
• : RU, FTN4, & STAT1 :: 25, 6,,,L
• : RU, FTN4, & GETFR :: 25, 6,,,L
• : RU, FTN4, & STAT2 :: 25, 6,,,L
• : RU, FTN4, & BHDXS :: 25, 6,,,L
• : RU, FTN4, & SZTAU :: 25, 6,,,L
• : RU, FTN4, & STAT3 :: 25, 6,,,L
• : RU, FTN4, & QSORT :: 25, 6,,,L
• : RU, FTN4, & STAT4 :: 25, 6,,,L
• : RU, FTN4, & STAT5 :: 25, 6,,,L
• : RU, FTN4, & STAT7 :: 25, 6,,,L
• : RU, FTN4, & STAT6 :: 25, 6,,,L

CDFPL
• : RU, FTN4, &CDFCC : 25, 6,,,L

NOISE
• : RU, FTN4, & NOISE :: 25, 6,,,L
• : RU, FTN4, & NOIS1 :: 25, 6,,,L
• : RU, FTN4, & BWCAL :: 25, 6,,,L
• : RU, FTN4, & ASINE :: 25, 6,,,L
• : RU, FTN4, & NOIS5 :: 25, 6,,,L
• : RU, FTN4, & NOIS2 :: 25, 6,,,L
• : RU, FTN4, & NOIS6 :: 25, 6,,,L
• : RU, FTN4, & PROB  :: 25, 6,,,L

CDFPL
• : RU, FTN4, & NOIS7 :: 25, 6,,,L
• : RU, FTN4, & FLDPL :: 25, 6,,,L
• : RU, FTN4, & PLOTC :: 25, 6,,,L
```

B.2.1 Makeup of Compile Instructions

The following instruction calls up the program to be run:

> : RU, FTN4, Source File :: Cartridge, Output LU, Relocate File, Number of lines per page, List*

The number of lines per page may be charged to a smaller number.

*List, the "L" may be changed to a "B" if no listing of the program is desired.

B.2.2 Loading Instructions

Before a program is run it must be loaded into the computer; once the program is loaded, it should not have to be reloaded unless the system is relocated or the files have been released. To load the program the instruction is of the form:

```
:*File name :: Cartridge, Terminal LU
  File names   · LDLMA
               · CDFPL
               · NOISL
                 DOTBF
                 SLOAD
                 NOISP
```

B.2.3 Running the Programs

The noise programs must be run in some order, because one program generates the data file for the next program. The nominal running order is:

RDLMA
NSTAT
CDFPL
NOISE
NOIS7

To run RDLMA the instruction form is:

RU, RDLMA, LU, JTAPE,

where:

LU = Logical unit of the terminal for questions.
JTAPE = Logical unit of tape drive where the data is loaded.

The noise-statistics (NSTAT) program is the second program and must be run before CDFPL, NOISE and NOIS7, because it prepares the data for each of these programs. To run the NSTAT program the instruction form is:

RU, NSTAT, 1G, 2G, 3G, 4G, 5G,

where:

1G = Terminal Logical Unit for questions; a positive LU number will print the output on the line printer and a negative LU number will route the output to your terminal.

2G = 0:do not accumulate data for CDF plot. In this case do not run CDFPL program as no file is created for the program.

= 1:Accumulated CDF data. A "1" should not be used on the 1st leg of each polygon.

= 2:Zero CDF data file then accumulate CDF data in file. This should be used for the 1st leg of each polygon.

3G = Logical unit number of tape drive for output tape. Should be zero (ϕ) if no output tape is desired.

4G = ϕ:restart $NOISE file use for first leg of each polygon

= 1:append the current $NOISE file. Use for all but first leg of polygon.

5G = Indicates which statistics to run:

xxxx0 - no k-s test

xxxx1 - run k-s test standard beams and frequencies

xxxx2 - run k-s test standard frequencies, user beams

xxxx3 - run k-s test user frequencies, standard beams

xxxx4 - run k-s test user beams and frequencies

xxx0x - no CDF test

xxx1x - run CDF on standard beams and frequencies

xxx2x - standard frequencies, user beams for CDF

xxx3x - standard beams, user frequencies for CDF

xxx4x - user beams, user frequencies for CDF

xx0xx - no auto-covariance

xx1xx - auto-covariance on user named beams

xx2xx - auto-covariance on user named beams

x0xxx - no cross-covariance

x1xxx - cross-covariance standard beams

x2xxx - cross-covariance user named beams

0xxxx - no rank-correlation

1xxxx - rank-correlation standard beams

2xxxx - rank-correlation user beams

Plus positive - run normal statistics
negative - no regular statistics

The CDFPL program is the third program and should be run only if 2G (NSTAT program) was not zero. The instruction form is:

RU, CDFPL, LU, flag,

where:

LU = Logical Unit of terminal.
flag = 1:plot a single leg.
2:plot cumulative polygon.

The NOISE program is the fourth program and must be run after "NSTAT" or it will have no data file to work on. The instruction form is:

RU, NOISE, 1G, 2G, 3G, 4G, 5G,

where:

1G = Logic unit number of the terminal

2G = 0 to use $NOISE file
1st two characters of data file

3G = 0 to use $NOISE file
2nd two characters of data file

4G = 0 to use $NOISE file
3rd two characters of data file

5G = Tape Logical Unit for copy of output and plot data file.

If 5G is negative the program will ask for angles to omit. If 5G is positive the program will use all of the beams.

EXAMPLE 1 - Skip beams using $NOISE as data file

RU,NOISE,1,0,0,0,-1,

EXAMPLE 2 - No beam skipping using $NOISE file

RU,NOISE,1,

EXAMPLE 3 - No beam skipping using $DATAF file

RU,NOISE,1,$D,AT,AF,0,

FILES USED:

$NOISE::25:3:24	(Median Levels)
$FITEN::25:3:24	(FORMATTED 10%)
$FTWFU::25:3:24	(FORMATTED 25%)
$RITEN::25:3:24	(Reformatted 10%)
$RTWFU::25:3:24	(Reformatted 25%)
$LITEN::25:3:24	(Binary field file 10%)
$LTWFU::25:3:24	(Binary field file 25%)
$AMDAT::25:3:31	(Output of NOISE)

The NOIS7 program is the final program. It generates directionality plots and uses a file generated by the NOISE program. The instruction form is:

RU, NOIS7, LU,

where:

LU = Logical Unit of the Terminal for questions.

FILES USED:

$AMDAT::25:3:31 (Data to be plotted)

*NPLTC::25:2:500:146 (Plot parameter)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